

# PETROGRAPHY OF PYROXENE GRANULITES FROM NORTHERN SWAT AND KOHISTAN

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## ABSTRACT

The pyroxene granulites of Swat and Kohistan, formerly called norites, form a part of an extensive belt stretching between Nanga Parbat and central Dir. They are relatively uniform in composition and usually represented by leucocratic rocks essentially composed of plagioclase, orthopyroxene and clinopyroxene, with subordinate amounts of quartz, opaque mineral(s), apatite, amphibole, biotite and, locally, garnet; but some of the rocks contain a higher proportion of amphibole and biotite. The proportion of quartz increases towards the intermediate members which may also have essential K-feldspar. The rocks are gneissose (foliated) and layered/banded, with some of the layers being pyroxenitic or anorthositic. Some of the bands are due to metamorphic segregation whilst others are relict igneous layers modified by metamorphism.

This paper presents a detailed account of the petrography of the rocks together with a discussion on the nature of the foliation, layering, and other aspects (xenoliths, hornblende-pegmatites, etc.), and details of the plagioclase in the granulite. Many of the features can be better explained by invoking metamorphism. It appears that the rocks crystallised plutonically from an andesitic basalt magma in an island arc or a continental margin, were metamorphosed (800°C, 7-8 kb) and finally intruded, as crystalline material capable of plastic flow, in the country rocks which were passing through amphibolite facies metamorphism.

## INTRODUCTION

The pyroxene granulites form a 30 km broad belt extending from the Nanga Parbat area through Indus and Swat valleys, and tapering into central Dir, beyond which they occur in isolated outcrops. To the south they are

bordered by the amphibolite belt in which are also found small outcrops of the pyroxene granulites. To the north, in Swat Valley, they are bordered by a belt of quartz diorites. The granulites were formerly called norites but petrographic and geochemical studies in the Swat and Indus valleys (Jan, 1977a, 1977b) favour a metamorphic origin for them. The rocks range from basic to intermediate in composition; norite is the principal rock-type but anorthosite and pyroxenite layers and bands, and hypersthene-quartz diorite types also occur. Retrograde amphibolitisation has taken place throughout the belt (see preceding paper).

Considerable confusion is found concerning the naming of granulites (Spry, 1969; Winkler, 1974). Strict application of the three most recently proposed nomenclatural systems for granulites (Mehnert, 1973; de Waard, 1973; Winkler and Sen, 1973) to the rocks of Swat forces one to use either an unnecessarily long and, to some extent, useless list of names, or complex names with prefixes. For this reason, the entire range of the granulites is collectively referred to in this paper as pyroxene granulites. However, the terms norite or noritic have been used for mafelsic members, and anorthosites and pyroxenites for the felsic and ultramafic members, respectively, purely for descriptive reasons and without genetic implications.

This paper presents a detailed account of the field features and petrography of the granulites with a view that this description throws ample light on the igneous versus metamorphic origin of the rocks. The study is based on over eight months of field work on the granulites of Swat and Indus valley, study of more than 300 samples in thin section and another 200 in crushed grains for quick appraisal of composition, and 80 chemical analyses of rocks and minerals. The geochemistry and mineralogy are intended for other publications but the plagioclase is being described in detail.

### MEGASCOPIC FEATURES

The pyroxene granulites range from basic to intermediate in composition. A characteristic field feature of these rocks is the flesh pink plagioclase. Where not pink, the rocks look greyish to dark gabbroic, turning light grey on weathering. A few of the rocks are very dark, locally 'greasy', and resemble the rocks of the charnockitic series. The dark colour in the latter is attributed to thin pale greenish or brownish yellow veins and stringers of iron oxide and hydroxide (Parras, 1958; Howie, 1967; Sahu *et al.*, 1973).

## Foliation

Most of the rocks are gneissose (foliated) and medium-grained (Pl. 1b), whilst some are coarse- and a few are fine-grained. In some of the rocks finer and coarser grained material is irregularly intermixed on a macroscopic scale. In the coarse-grained types occurring in the vicinity of Madyan and to the south, lens-shaped grains or clusters of small grains impart to the rocks the look of augen gneisses. The foliation trends E-W to NE-SW, with steep to moderate northerly dips throughout the Indus valley (except in the south where the rocks lack distinct foliation) and the southern part of the Swat valley. Further north in Swat, the foliation changes from NE-SW to N-S to NNW-SSE, with moderate to steep dips changing from NW to W to SWW (Jan and Mian, 1971). Thus if the Swat rocks are considered separately, their foliation suggests that they may have the shape of a funnel. Such an interpretation, however, should await the investigation of the western part of the Swat valley.

The origin of the foliation is not clear and can be explained in a number of ways. It might be igneous flow structure, as exhibited by some plutonic and volcanic rocks; such features have been widely reported from alpine-type mafic-ultramafic complexes (Thayer, 1963), from large areas of anorthosite in southern Angola (Simpson, 1970), and some other areas (e. g., Adirondacks, Buddington, 1939). If the foliation in the Swat rocks is of igneous origin, it would require that the material was either emplaced plastically as a crystalline mush or that the magma carried a very high proportion of crystalline material. On the other hand, the foliation could be a product of regional metamorphism, such as occurs in other high-grade metamorphic terrains. The augen-like, gneissose structure of some norites can be explained better if stresses during metamorphism were involved.

A third possibility is that the Swat rocks either formed under granulite facies conditions from an appropriate magma, or they were solidified masses of plagioclase norites that were remobilised at depth and emplaced in their present environment during granulite facies metamorphism. Temperatures of 700°-800°C have been estimated from the study of fluid inclusions in some granulite facies rocks from Norway and Madagascar (Touret, 1971; Berglund and Touret, 1976), whereas Wood and Banno (1973) and Sexena (1976), from thermodynamic reasoning, have calculated temperatures of around 800°C for charnockites and pyroxene granulites. These temperatures are in accordance with those deduced from magnetite-ilmenite equilibrium for the late stage oxide minerals of the Adirondake anorthosite magma (Buddington and Lindsley, 1964) and are

probably not significantly lower than those operating during the last stages of all basic to intermediate magmas. Sighinolfi and Gorgoni (1975) think that the massif-type anorthosites formed from magmas of suitable composition that underwent extremely slow cooling under high-grade metamorphic conditions.

### Layering and banding

The pyroxene granulites of Swat and Dir valleys display some degree of compositional layering parallel to foliation (Pl. 2b). This is not a common feature in the Indus valley, however; but the latter area has not been investigated in sufficient detail to yield a final conclusion about the layering phenomenon. Shams (1975) has reported light- and dark-coloured rhythmic bands from norites of Thak valley. Most of the layers in Swat are noritic; however, anorthositic layers are also frequent while pyroxenitic layers are rare (Jan and Kempe, 1973). The anorthositic layers are generally thin, ranging from mere streaks to a few centimetres in thickness, but a few are up to a third of a metre thick. The pyroxenites, on the other hand, range from streaks to 3 m thick layers often in 'zones' that may be up to 20 m thick (e.g., at Pardesha, 2 km west of Madyan; Pl. 2a). The contact between the adjacent layers may be sharp or gradual; the extreme types (anorthosites and pyroxenites) have not been found interlayered. In rare cases, the pyroxenite layers contain thin veins of noritic material, whilst phase layering (Hess, 1960) is almost non-existent in Swat.

The layering generally diminishes laterally over a distance of only a few metres. This is in marked contrast to the layering in stratiform complexes where even the thin layers are persistent over long distances (Jackson, 1967; Wager and Brown, 1968; Wadsworth, 1973). On the other hand, layering of this type has been reported from alpine-type mafic-ultramafic rocks (Thayer, 1960, 1963) with one major difference only: that the layering of the alpine-type rocks is generally discordant (Jackson and Thayer, 1972). The thick ultramafic zones may extend for some hundred metres. The anorthositic layers may gradually pass into noritic rocks or they may form flattened biconvex lenses in the norites. Bowes and others (1964) have regarded this wedge-shaped bedding to be of non-metamorphic origin and a common feature of the layered complexes. Brown (1964), however, thinks it to be a relatively rare feature confined to the marginal or other specific parts of the intrusions.

In a few noritic rocks the pyroxene is in large grains, or concentrated in aggregates, up to 8 mm across, locally arranged in 'trains' parallel to the foliation and thus imparting some degree of layering. In some places, distinct banding (or layering) has resulted due to variations in the grain-size of both mafic and felsic minerals in the alternate bands that may be up to several centimetres thick. It is worth mentioning that the grain-size variation in the neighbouring bands is in many cases so abrupt and large (up to  $2\frac{1}{2}$  times) that it does not look to be size-graded layering as found in the stratiform complexes. Also, in contrast to the easily noticeable bands in Swat rocks, size-graded layering, according to Jackson (1967), is difficult to see in the field. Layering imparted due to variation in grain-size of coarse grains or clots of pyroxene has been described from some anorthosite complexes, and Hargraves (1962) has also reported layering due to size variations in poikilitic pyroxene in the Alard Lake, Quebec, anorthosites.

The short lateral extent of the layers in the Swat rocks is considered by the writer to be of petrogenic significance. The layers may be *in situ* differentiated rocks that have been distorted and deformed by metamorphic and tectonic activity; they may be the products of metamorphic differentiation or metasomatism as suggested by Sorensen (1967) for some small ultramafic bodies in Greenland and elsewhere; or they may have been distorted during the emplacement of a largely solid mass of layered norites-anorthosites capable of plastic flow under granulite facies conditions. Although the streaks and some thin bands of anorthosite and pyroxenite may have been produced by metamorphic differentiation, much of the layering does not seem to be due to this process because, (1) it cannot satisfactorily explain the anorthositic and ultramafic layers having sharp contacts with the enclosing norites; (2) the origin of the anorthosite layers cannot be separated from that of the pyroxenite layers; to form a 20 m thick pyroxenite-norite zone would require considerable transfer of material and one would expect complementary anorthosites on the margins of such zones; and (3) the writer has not been able to find in the literature any examples of bodies of the size and shape of the Swat pyroxenites considered to result from metamorphic differentiation. Nor can he offer any explanation other than deformation/metamorphism for the production of the layering due to grain-size variations; he is not aware of such a phenomenon in stratiform complexes.

In a few places the noritic rocks contain concordant or discordant veins of coarse-grained anorthosite. These seem to be metamorphic in origin, there is no evidence to suggest that such bodies are a product of magmatic crystallisation. Chaudhry and others (1974) have described oval-shaped pyroxenites with sharp contacts in norites of Dir. The general mode of these rocks is similar to the pyroxenite layers. These rocks have been interpreted to be earlier differentiated pyroxenites of the norite magma some of which were picked up by the magma as screens whilst others were intruded in the norites (? plastically during metamorphism or tectonically). Metamorphosed pyroxenites and bahliaite intrusions also occur in the Swat valley. These rocks are different from the pyroxenite layers in norites and may have been emplaced as plastic material from some deeper source.

#### **Pegmatites and veins in the granulites**

An interesting feature of the amphibolites and, especially, pyroxene granulites of the area is the occurrence of hornblende-plagioclase pegmatites up to 5 m thick and, locally, unusually coarse-grained (Pl. 1b). Some of them contain quartz, mica, and sulphides occupying the space between large crystals, a few of such pegmatites having finer-grained margins. Others are mica-free but may, in rare cases, contain garnet (in some abundant) and/or epidote. The feldspar may be altered to a hard pinkish or greenish material and the size of different crystals of a mineral may vary greatly. Hornblende-plagioclase pegmatites have been described from South Harris (Dearnley, 1963), and some other places. The coarseness of the rocks is better displayed by hornblende crystals which reach 50 cm in length and 25 cm in width, and at places contain coarse inclusions of quartz and feldspar. The hornblende usually grows at high angles to the walls but in a few it is subparallel to the walls. Some of the pegmatites, 4 to 8 cm thick, contain pencil-like hornblende crystals over 12 cm long and 1.2 cm broad. The distribution of hornblende and plagioclase is selective in some cases and either of the two may be concentrated in the centre of the body, or in one or both margins.

There are all gradations from hornblende-rich to feldspar-rich types although in most cases both of the minerals are important constituents of the pegmatites. The largest of the pegmatites occurring 5 km north of Matta, Upper Swat, is over a thousand square metres in area. It is composed mainly of tschermakitic hornblende with varying amounts of epidote and

green chlorite, and minor opaque minerals, rutile and pyrite. Similar pegmatites to the south of Matta may contain garnet, locally in large crystals or aggregates. Such dark hornblende-rich pegmatites may be cut by hornblende-plagioclase pegmatite dykelets and they may have small peridotites and pyroxenites on their margins. 'Hornblendites' of this type are more abundant in the amphibolites of Dir to the west of the area (Kakar *et al.*, 1971). In a number of cases, considerable amphibolitisation has taken place around the pegmatites, in some cases up to 2 m, the main product being abundant amphibole (? hornblende).

The variations in mineral assemblage and in the proportion of hornblende and plagioclase in different pegmatites, and their presence in amphibolites as well as norites, suggests that they have not been derived from a late magmatic silicate phase although Shams (1975) considered the Thak pegmatites to be igneous. The Swat pegmatites appear to have formed during the amphibolite-grade metamorphic conditions by the metasomatic action of hot watery solutions on the rocks. In the case of the granulites, they may have been the solutions (essentially water) which were being expelled while the rocks were being recrystallised into essentially anhydrous assemblages, or they may be from some other source after the rocks had already recrystallised. It is possible that some of the pegmatites were later remobilised and emplaced as intrusive masses in their present environments. Hornblende pegmatites of metasomatic origin have been reported from an alpine-type mafic complex at Canyon Mountain, Oregon (Thayer and Himmelberg, 1968). Barth (1950) has described hornblende-rich norite from southern Norway which "formed by supercritical water vapour streaming through cracks in the norite" followed by further pneumatolytic action that produced bahaite. Green and Mysin (1972) attributed the formation of hornblende-plagioclase pegmatites from western Norway to partial melting of gneisses adjacent to eclogites in a high pressure metamorphic terrain. Kakar *et al.*, (1971) have reported some 'hornblendite' bodies to be over 25 sq. km in western Dir and "definitely intrusive in nature, at least partially" and "seem to have directly crystallized from extremely dilute hydrous solutions under high pressures".

In addition to the hornblende pegmatites, abundant secondary veins containing varying combinations and proportions of amphibole(s), feldspar, epidote, quartz, opaque minerals, calcite, chlorite, serpentine, talc, mica, sphene and, rarely, (?) rutile and garnet are spread throughout the norites

(Fig. 1) and to a lesser extent the amphibolites. Most of them are less than a centimetre thick and, at places, closely-spaced. In rare cases, abundant amphibole develops in the norites up to a distance of 3 cm from the veins. Microscopic examination of some of these veins suggests that they represent assemblages in the greenschist or lower part of the amphibolite facies. Greenish-coloured sheared zones up to 15 m thick, and slickensides coated with yellow green epidote, chlorite and/or quartz, are common. Granitic rocks (discussed in a separate section), quartz veins up to a metre in thickness, and simple pegmatites containing feldspar, quartz and lesser amounts of white mica and/or vermiculite and, rarely, garnet also occur in the granulites. In rare instances, the rocks are cut by thin dykelets (Pl. 1b) composed of plagioclase, two pyroxenes and abundant hornblende. They are also granulitic in texture and may be related genetically to the granulites.

### Xenoliths

Xenoliths (composed of plagioclase and augite with minor amounts of other minerals but no hypersthene) have been noticed very occasionally in the granulites but a careful search is needed in case their presence helps some conclusions to be reached about the temperature of the rocks at the time of emplacement in their present environments. The occurrence of amphibolitic and silicic xenoliths in Kana stream has been noted but the host rocks here are amphibolitised norites and valid assessment of further contact metamorphic effects on the xenoliths is difficult. The occurrence of large bodies of amphibolite 'trapped' in the granulites along Kedam stream and near Asrit has also been mentioned in the paper on amphibolites. In both of these localities the mineral assemblages are typical of the amphibolite facies. Large masses of biotite gneiss occurring in the granulites of Mankial area again do not show metamorphism beyond the amphibolite facies and the rocks are composed of quartz, biotite, altered feldspar, amphibole and epidote. A body of low-grade metasedimentary rocks, exceeding  $10 \times 3\frac{1}{2}$  km in size and apparently enclosed in the granulites-amphibolites along the Kandia river, has been described by Jan (1970).

Whether the Swat norites are magmatic rocks *in situ*, or recrystallised granulites, one would expect a higher grade metamorphism than is exhibited, so far as the available evidence indicates, by the xenoliths within them. Either the intruded magma (and subsequent granulite facies metamorphism)

was unable to drive out water from the enclosed rocks to produce anhydrous assemblages which are the usual indicators of higher than amphibolite grade metamorphism in basic rocks or, less likely, the present assemblages are retrograde. However, it is also possible that the granulites at the time of emplacement (? as crystalline mushes) had already lost much of their heat so that they could not produce mineral assemblages of a higher grade than those already present.

A (?) hybrid rock outcropping 5 km west of the Swat river in Asrit stream is worthy of mention. It contains bytownitic plagioclase, quartz, reddish-brown and pale green biotite, pink garnet (locally up to 25%), strongly pleochroic hypersthene, opaque minerals, and secondary chlorite and muscovite, and is confined to the marginal parts of a small granitic rock associated with the granulites and banded amphibolites. The hypersthene, biotite, and, to a lesser extent, garnet are poikiloblastic and inclusions of biotite in the garnet suggest that the biotite is not a retrograde product. Field relations, the occurrence of garnet (which has not been noticed in the norites of Swat valley) and calcic plagioclase, and the mineralogy of the rock are too complicated to lead to any conclusions at this stage.

## FEATURES OBSERVED IN THIN SECTION

### Mode and texture

The pyroxene granulites, in contrast to the Jijal garnet granulites, are relatively uniform in mineralogy. They are composed essentially of plagioclase, hypersthene, and clinopyroxene, with smaller amounts of quartz, opaque minerals, amphibole, biotite, and apatite. The amount of quartz increases in the intermediate members which also contain K-feldspar. All the rocks except pyroxenites, generally, have a rather low colour index ( $< 30$ ) and most, by analogy with Buddington's (1939) classification of the Adirondacks anorthositic rocks, can be called feldspathic norites. With rare exceptions, the total volume of hornblende and biotite is less than 2% while the opaque minerals are less than 3%. The amount of the former two minerals in Dir norites (Chaudhry *et al.*, 1974; Malik, 1975) is a little higher due possibly to a greater degree of alteration. The amount of apatite is slightly more than that reported for most of the rocks in Table 1; it seems that tiny inclusions of apatite in other minerals have been ignored in the counting.

TABLE 1. MODAL COMPOSITION OF PYROXENE GRANULITES

Sample No.	No. of points counted	Thin section(s)	Plg	Opx	Cpx	Qz	Ore	Ap	Amph	Bio	Others
US 9	3570	1	75.2	14.2	6.0	2.5	1.2	0.3	0.3	0.2	0.1
SI 182	5240	2	71.0	13.0	11.8	...	2.1	0.5	0.9	...	0.6
SI 188a	8799	1	72.0	12.3	9.6	0.1	4.8	0.4	0.2	0.1	0.6
SI 188b	5090	2	71.7	14.3	7.8	...	5.3	0.9	Tr	0.1	...
SI 190	7367	1	70.0	7.2	7.5	0.4	5.8	0.3	7.5	0.3	1.0
SI 192	4419	2	75.8	13.7	7.2	1.0	0.5	0.1	1.1	0.6	...
SI 193	2974	1	69.9	7.3	8.1	10.0	3.0	0.5	Tr	0.7	0.4
SI 196	14801	2	67.4	13.7	11.1	1.9	4.5	0.3	0.8	0.3	...
SI 197	5732	2	63.1	11.6	8.3	1.4	2.8	0.4	8.8	0.7	2.9
SK 301	7103	1	73.4	13.1	8.7	1.6	1.6	0.1	1.1	0.5	...
SK 322	8863	1	58.5	22.1	16.0	0.7	2.3	0.1	0.3	...	...
SI 337	14618	2	60.3	20.0	11.4	4.6	1.9	0.1	1.4	Tr	0.3
SK 422	12314	2	69.9	10.7	7.0	7.4	2.3	0.4	0.2	1.9	0.2
SK 521	9023	1	65.0	12.9	10.1	8.4	2.3	0.3	...	0.9	Tr
SK 528	4971	1	64.3	19.0	9.6	4.9	1.4	0.2	0.4	0.2	0.1
SK 592	5513	1	62.3	6.8	3.2	18.0	1.0	0.2	3.2	4.6	0.7
SK 600	11021	2	71.1	16.1	9.9	1.0	1.4	Tr	0.5	Tr	...
SK 615	6947	2	74.7	10.3	4.3	6.6	2.2	0.4	...	1.4	...
ANORTHOSITE AND PYROXENITE MEMBERS											
KDM	5785	1	93.6	0.9	2.1	2.6	0.6	0.2	...	...	...
SK 315	9302	1	19.9	39.9	34.2	0.4	0.6	...	0.5	0.3	4.2
SK 340	2960	1	8.7	75.4	8.4	Tr	0.3	...	7.2	...	...

Samples with prefix SK are from Swat Kohistan, with SI from the Indus valley, US 9 from Upper Swat, and KDM from Kedam.

Most of the rocks are medium-grained, gneissose, and 'hypidioblastic' to xenoblastic, with straight to curved, more rarely lobate or dentate grain boundaries. Triple points and polygonal grain growths are not uncommon, the latter especially in the case of smaller pyroxene grains (Pl. 2c, d). Smoothly curved interfaces and polygonal grain shapes in the mafic gneisses of Broken Hill, Australia, have been regarded by Vernon (1965) to suggest that the grains have undergone growth and adjustment in the solid state. A few of the rocks show moderate to intense cataclasis in thin section, with porphyroclasts enclosed in a crushed matrix. In many rocks the minerals are strained; they have non-uniform extinction, microfractures and, in some cases, the grains are bent (Pl. 3a; 4a). The coarse-grained rocks near Madyan have lens-shaped grains or aggregates of plagioclase and pyroxenes, the rocks resembling augen gneisses.

The textures of the rocks are thus suggestive of deformation as well as metamorphism and closely resemble those of granulites, anorthosites (except for the much coarser grain size of the latter), and alpine gabbros. Cumulate and ophitic textures, so typical of the stratiform complexes, are virtually non-existent. Further, the writer has not been able to establish any sequence of crystallisation; in most rocks, crystallisation of plagioclase, ortho- and clinopyroxene, and quartz seems generally to have occurred simultaneously.

### The Plagioclase

The plagioclase is fairly fresh or slightly cloudy along grain boundaries, fractures and internal spots (Pl. 4a), but in a few rocks almost all of it is clouded. Inclusions of pyroxene and opaque minerals are common but not abundant; in a few rocks the larger grains of plagioclase have frequent inclusions of opaque minerals and, rarely, some biotite although the margins may be inclusion-free. Whether or not the frequent inclusions are premetamorphic is difficult to assess, but the biotite inclusions were probably produced during metamorphism by reaction between some ferromagnesian inclusions and the potassium content of the plagioclase. Since biotite is very restricted in occurrence in the rocks and, in a few cases, is present only in the form of inclusions in the plagioclase (Pl. 3b), a metasomatic/replacement origin does not seem plausible. In some rocks the plagioclase contains an acicular, brownish to black, opaque mineral (? ilmenite), and also rutile. The latter has not been recorded as a stable phase outside the plagioclase in any of the rocks. Probably significant from the petrogenetic point of view are tiny rounded inclusions of quartz in the plagioc-

ase, in a number of rocks. Their anhedral outlines suggest that they have either been incorporated in the plagioclase during metamorphism or, less probably, they are primary (magmatic) inclusions of a silica mineral that have been recrystallised along with the enclosing plagioclase during metamorphism.

Although none of the plagioclase has been chemically analysed, its composition seems to have a restricted range. Determination in 60 rocks of maximum symmetrical extinction angles in sections normal to (010), and measurement of the refractive index in ten of these 60 plagioclases, suggest that the plagioclase ranges from  $An_{46}$  in the intermediate members to  $An_{54}$  in the basic members. In some, compositions as calcic as  $An_{60}$  have been found from extinction angles. (The An content determined by extinction angle has been found to be slightly higher than that determined from refractive index. Crosby, 1968, also found a similar small difference in the anorthite content determined by the two methods). The composition of the plagioclase in the anorthosite members also falls within this range. However, Jan and Kempe (1973) reported the An content of the plagioclase to be 42, determined by refractive index on (010) cleavage fragments, in an anorthosite vein in the norites. This narrow range is akin to the plagioclases found in the Adirondack (Buddington, 1939) and other anorthosite massifs, although Crosby (1972) has warned against "making sweeping generalization". The narrow range of plagioclase composition in the anorthosites has been attributed in large massifs to narrow temperature interval, narrow range of load or water pressure, and/or close approximation to chemical equilibrium during slow crystallisation of the magma (Buddington, 1969; Yoder, 1969; Crosby, 1972). The An content of the plagioclase from the norites of central Dir (Chaudhry *et al.*, 1974) ranges from  $An_{42}$  to  $An_{60}$  but in Rabat area of Dir the plagioclase is reportedly more calcic,  $An_{60-70}$  (Malik, 1975). Shams (1975) reports a range of  $An_{46}$  to  $An_{68}$  in the noritic rocks of Thak valley.

In a number of sections, some grains of the plagioclase have been found to be usually partially, but in some cases entirely, antiperthitic (Pl. 3c). Different orientation or submicroscopic size may be the reason for the apparent lack of this phenomenon in the other grains within a section. In rare cases the plagioclase is antiperthitic along certain compositional zones. The K-feldspar is in rhombic to angular beads, seemingly a product of exsolution and, in at least some cases, connected with straining (deformation). Antiperthitic plagioclase is uncommon in basic igneous rocks but has been reported from many pyroxene granulites and charnockites (Parras, 1958). Hubbard

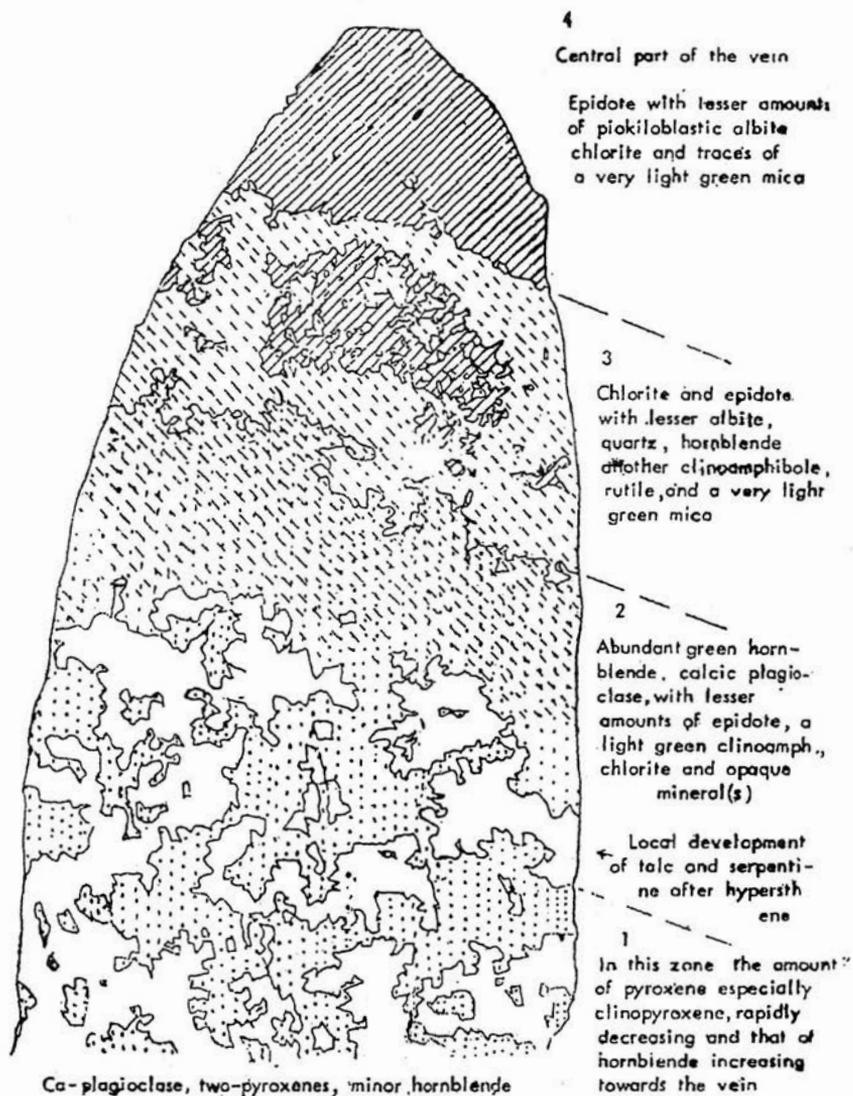


FIGURE 1. Simplified sketch showing mineralogical changes from fresh rock up to the centre of a secondary vein X 4 natural size (Drawing by D. Moore)

(1965) reported that the antiperthitic plagioclases of the enderbites from SW Nigeria are always twinned. In the Swat rocks, the antiperthitic plagioclases may or may not show twinning. However, according to a number of authors, most of the twinning in metamorphic plagioclase is produced by deformation, whilst Chayes (1952) has shown the close relationship between deformation and exsolution.

Twinning is well displayed by most plagioclases of the Swat pyroxene granulites. Although the phenomenon has not been studied by the more satisfactory universal stage technique, the suggestions of various workers regarding the distinction between the three common types of twin laws were followed and some general conclusions can be reached. Although Howie (1955) states that "until more is known about the cause and mechanism of twinning it would be dangerous to consider the plagioclase twin laws as being diagnostic of the history of the rocks", Turner (1951), Gorai (1951), Rao and Rao (1953), and Tobi (1961, 1962) have shown that there are differences in the twin laws of igneous and metamorphic plagioclases. Twinning in the metamorphic plagioclases is reportedly much less common than in igneous ones and, when present, is according to one law only, usually albite or pericline/acline, and only rarely Carlsbad. "Growth twins in igneous crystals are commonly complex; abundant individuals and a variety of twin laws may be present in one crystal" (Spry, 1969). Some of the pyroxene granulites of Swat appear to have hardly any twinned plagioclase whilst in a few there are large crystals containing many twin lamellae. In most cases the individual twin lamellae do not maintain a constant thickness and gradually thin out, some fading away without extending along the entire grain whilst a few are enclosed within the grains. Lamellar twins of this type in the plagioclases of the mafic gneisses of Broken Hill, Australia, have been considered by Vernon (1965) to be mechanical in origin. He writes, "gradual changes of interface direction form a reliable criterion of mechanical twinning in polycrystalline aggregates" and "to minimize lattice strain they taper".

Most plagioclases of Swat granulites are twinned according to one law only; however, combinations according to the albite-pericline/acline, a few Carlsbad-albite and, very rarely, Carlsbad-albite-pericline/acline laws have also been noted. The complex twin combinations involving the Carlsbad law are very rare or absent in metamorphic plagioclases and the Swat rocks also show them only in rare cases. Possible explanations for those from Swat

may be: (1) the Carlsbad law is inherited, i. e., relict or premetamorphic, or (2) the albite law has been mistaken for the Carlsbad law (cf. Turner, 1951; Tobi, 1959). It thus appears that in the Swat plagioclases also twinning is less common and less complex than in igneous plagioclases, and the twins may have grown under metamorphic conditions. The difference in twinning of plagioclases from the two environments has been considered by the authors cited above to reflect differences in physical conditions: temperature, and liquid versus solid as the medium of crystallisation. According to the French theory of twinning (Donnay; 1943), differences in twinning behaviour in similar minerals are probably due to differences in space lattice structure rather than to the direct influence of external conditions such as temperature. However, it is thought here that the space lattice structure may itself be influenced by external conditions.

Zoning of the plagioclases is uncommon in the pyroxene granulites of Swat and, when present, is mostly marginal. A few of the rocks contain plagioclase with multiple zoning but the anorthite content does not seem to vary greatly within them. Although zoning is a more common feature of igneous rocks, it has also been noted in metamorphic rocks (Misch, 1955; Cannon, 1966). Zoned plagioclases from the garnet granulites of Jijal have already been mentioned in a previous paper. There is a possibility that zoning in the pyroxene granulites of Swat is of metamorphic origin, although in most cases it is confined to rather large plagioclase grains containing frequent opaque inclusions and may thus be premetamorphic in origin. In some of the rocks, myrmekitic intergrowths between quartz and plagioclase margins have also been noted. Although a great majority of workers regard myrmekite as being replacive in origin (Binns, 1966; Deer *et al.*, 1966), Shelley (1964) thinks that it is formed by the incorporation of recrystallising crushed quartz in growing sodic plagioclase exsolved from orthoclase following marginal cataclasis. Parras (1958) has also suggested an exsolution origin for myrmekite in charnockites. Micropegmatitic textures have not been noticed even in those Swat rocks that are comparatively high in  $\text{SiO}_2$  and  $\text{K}_2\text{O}$  (i. e., the intermediate members).

#### The K-feldspar

The K-feldspar is noticeable in independent grains in those rocks which contain more than some one percent of  $\text{K}_2\text{O}$  and do not have substantial biotite

and hornblende. It shows microcline twinning in a few rocks only so that most of it may be orthoclase; thus in small grains it is difficult to distinguish from quartz and untwinned plagioclase. In almost all cases it is perthitic and contains thin strings and hair of exsolved plagioclase (Pl. 3d).

### The Pyroxenes

Hypersthene, after plagioclase the next most abundant mineral, ranges in composition from  $En_{64}$  to  $En_{54}$ , but in some pyroxenite members it is bronzitic. In the Thak valley noritic rocks, Shams (1975) has reported a composition range of  $En_{77}$  to  $En_{65}$ , determined optically. Like the orthopyroxenes of the granulite facies (Howie, 1965), it is strongly pleochroic, with a pink,  $\beta$  yellowish, and  $\gamma$  green. The clinopyroxene is green, weakly or non-pleochroic, and covers even a more restricted range of composition than the coexisting hypersthene, clustering around  $Mg_{37} Fe_{17} Ca_{46}$  in the augite-salite fields. Average composition of the clinopyroxene from Thak valley, determined optically by Shams (1975), is  $En_{45} Fs_{14} Wo_{41}$ . The pyroxenes of one rock (SI 221) depart slightly from these values, with clinopyroxene being  $Mg_{37.2} Fe_{23.7} Ca_{39.1}$  and orthopyroxene falling near the border between hypersthene and ferrohypersthene ( $En_{51.4}$ ). This rock has been collected from the northernmost part of the area investigated along the Kandia river and it is not clear whether or not it is genetically related to the rest of the granulites. Both pyroxenes locally contain exsolution lamellae and irregular blebs of the other pyroxene. These lamellae are not as regularly spaced, continuous, and of uniform thickness as those in igneous pyroxenes (see Poldervaart and Hess, 1951) and in some cases the exsolved material seems to be concentrated in the most deformed parts of the crystals. Perhaps equally or even more common are thin brown to brownish-black blades, seen in both ortho- and clinopyroxenes. Jan and Kempe (1973) thought them to be iron oxide and the present study confirms this. The ore blades and exsolved pyroxene may occur in the same or different grains.

With rare exceptions, the pyroxenes do not show ophitic texture or reaction rims although they may contain inclusions of each other, plagioclase, opaque minerals, and quartz. In some rocks (as in SK 615) the comparatively small grains of pyroxene develop into typical polygons. In a few rocks the clinopyroxene is twinned and in rare cases it has multiple twin lamellae. Non-uniform extinction due to straining is not uncommon and a few of the grains are bent.

In most cases the pyroxenes are either fresh or, more so in the case of hypersthene, only slightly altered along grain margins, fractures, and cleavages. The alteration product is normally serpentine (rarely talc) and magnetite. In a few the alteration is intense and covers the whole grains, and the serpentine may be enveloped by a green amphibole. In some cases the alteration is mainly to a fibrous amphibole  $\pm$  iron oxide, while in a few the pyroxene (especially clinopyroxene) may be replaced by a hornblendic amphibole. This latter alteration seems to be a higher-grade retrogressive alteration than the other types mentioned. In some cases the pyroxenes have reacted with the plagioclase marginally, the orthopyroxene having developed a thin colourless amphibole (? or clinopyroxene) envelope surrounded by one of green amphibole (Pl. 2d), while the clinopyroxene is separated from the plagioclase by an irregular and comparatively thicker epidote (? and quartz) envelope. In a few a blue-green amphibole envelope may occur between the epidote and clinopyroxene.

### The other minerals

The opaque minerals are represented by magnetite but all the rocks also contain ilmenite; some of them also contain a sulphide phase, probably pyrite. In addition to their occurrence as inclusions and independent subhedral grains, they occur in a few rocks typically filling the interstices and in some of these appear to form 'poikilitic' patches. No polished sections have been studied to determine their mutual relationship; however, the occasional alteration of magnetite to a reddish material, and that of ilmenite to sphene or leucoxene, coupled with their different magnetic susceptibilities during separation, suggest that the two minerals occur mainly as independent phases. In rare cases they carry inclusions of other minerals, including quartz. The quartz is usually anhedral, strained, and, in rare cases, subpoikilitic.

Brownish green pleochroic amphibole and deep reddish brown mica occur in most rocks in small quantities but a few rocks have only one of the two minerals. Of the three such amphiboles analysed, two are tschermakitic hornblendes and one is ferroan pargasite. The mica, on the basis of two partial analyses, is common biotite. Some of the rocks contain an abundant quantity of one or both of these minerals. The biotite, extending as digitations and in some cases cutting through other minerals, is secondary (Pl. 5a); however, it is difficult to make such a generalisation concerning the amphibole. The latter is usually poikilitic and sieved with quartz; it may surround pyroxene

or opaque minerals and, in a few cases, is intergrown with biotite. In some of the rocks the amphibole is more abundant than pyroxene; it has been noted in a number of cases that with an increase in its content the proportion of pyroxene falls. In SI 221 (Pl. 4c), the amphibole is clearly replacing the pyroxene marginally as well as along cleavages. It thus appears that at least some, if not all, of the amphibole is secondary in origin. Most of the biotite contains intergrown quartz and may surround opaque minerals. It occurs in isolated plates or poikilitic patches but, in some cases, it grows radially into symplectic intergrowths containing myrmekite towards the edge.

Garnet has not been found except in some rocks, which contain abundant hornblende, to the north of Soe, west of the Indus river. The occurrences, in some, of garnet-hornblende-plagioclase pegmatites and garnet-bearing veins suggest a high temperature metasomatic origin for these; however, the rocks are slightly different in chemistry from the remaining granulites and a primary metamorphic origin cannot be totally rejected for the development of garnet in the rock itself. Secondary scapolite after plagioclase has been noted in two of the rocks (SI 182 and SK 346) and a few alteration veins. A few of the rocks contain traces of calcite while the intermediate members may have a little zircon.

#### **The ultramafic and anorthositic members**

The pyroxenite and anorthosite members are similar to the noritic rocks except in their content of mafic/felsic minerals. The anorthosites usually carry some quartz while the pyroxenites (commonly websterites but in some rocks one type of pyroxene may predominate) some 'interstitial' plagioclase. Olivine has not been found in any of the granulites. Of special interest is the anorthosite SI 185 which was collected in the field as 'a minor intrusion of epidote-bearing syenitic rocks' in the norites along the Indus valley road. It is composed of plagioclase, epidote, quartz, chlorite, and 'sphenised' ilmenite. The plagioclase is completely altered to zoisite and sericite but the two are rarely intergrown, the sericitic material apparently having migrated towards the margins of the grains. The rock contains a yellowish epidote, usually coarser-grained than the zoisite and often forming clusters. It may be an independent intrusion, or a thick autochthonous or remobilised layer genetically related to the granulites. Chemically, however, it is significantly different from the anorthosites forming layers in the pyroxene granulites.

### The minor granulites in the amphibolite belt

Finally, rare and small isolated outcrops and lenses of fresh to altered pyroxene granulite occurring in the epidote amphibolite belt are worthy of mention. Whether or not these rocks are genetically related to the rest of the pyroxene granulites is difficult to answer at this stage. One such body occurs near Patan, more than 20 km from the main mass of the granulites. However, texturally, mineralogically, and chemically these rocks do not differ from the rest of the granulites (Pl. 4b). Although they are dealt with here only superficially, due to lack of detailed field data, in the writer's opinion an understanding of these rocks may be essential to any theory on the petrogenesis of the main mass. If these rocks are genetically related to the latter then their occurrence in amphibolites poses some serious questions: (1) have the rocks escaped amphibolite grade metamorphism that affected the surrounding rocks?; (2) were they emplaced (? as plastic material) after the country rocks had been metamorphosed to amphibolites?; or (3) are these rocks and the main pyroxene granulites in fact igneous bodies that have not undergone the granulite grade metamorphism? The evidence of high-grade metamorphism presented in the previous pages does not favour a primary igneous origin for the rocks although Shams (1975) regarded the norites near Chilas to be igneous and Jan and Kempe (1973) tended to this opinion.

### CONCLUDING REMARKS

The pyroxene granulites are basic to intermediate in composition; no charnockites have so far been found in the belt. They were derived from a tholeiitic (andesitic basalt) magma, either in a continental margin during the Archaean as part of a major crust-building activity, or at a later date in an island-arc type location. Since then they have suffered polyphase metamorphism and deformation and were probably intruded in their present environments as remobilised crystalline material capable of plastic flow. At the time of their final emplacement they had sufficiently cooled down so that they could not produce a higher than the amphibolite facies metamorphism through which the country rocks were passing. During their upward transport they had access to water and local amphibolitisation took place, especially at their southern margin in the Madyan-Fatehpur area.

Based on various methods of geothermometry, high temperature-pressure experiments on rocks of similar composition, and other considerations, it is

thought that the pyroxene granulites formed under relatively uniform TP conditions of about 800°C and 7-8 kb. Such a uniformity of metamorphic conditions over a vast area of some thousand square kilometres is a little strange. However, it is supported by the uniformity in the  $K_D$  Mg-Fe in 17 pyroxene pairs analysed, in their tie-line intersections on Wo-En join of the pyroxene triangle, and by the uniformity of their pyroxene and plagioclase compositions.

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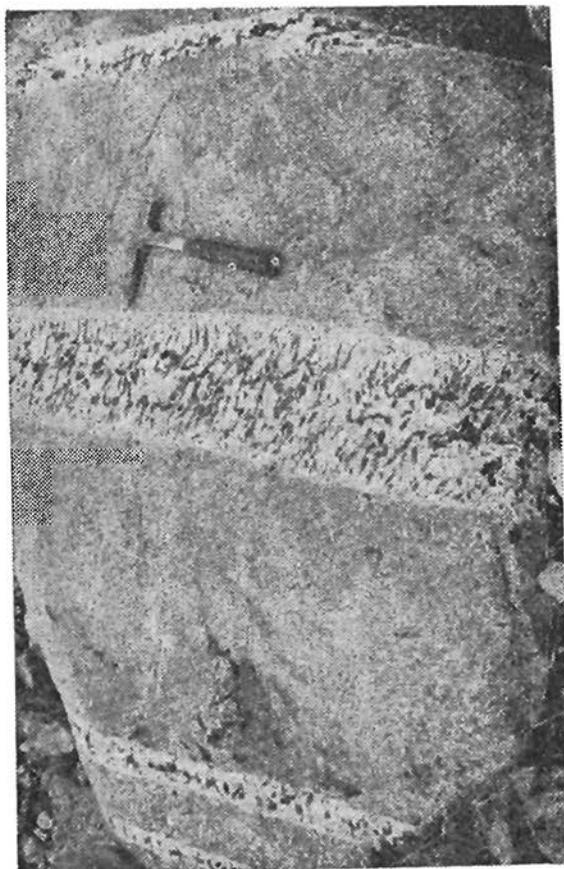
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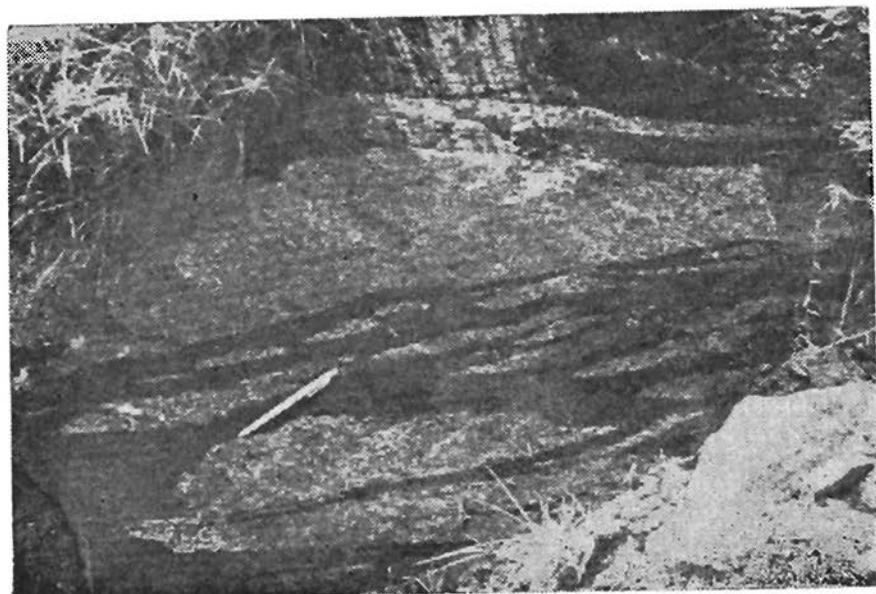
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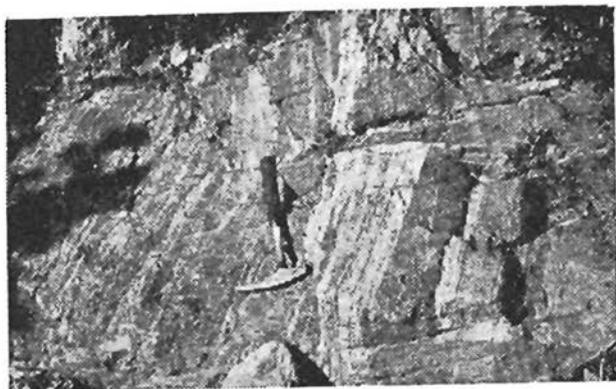


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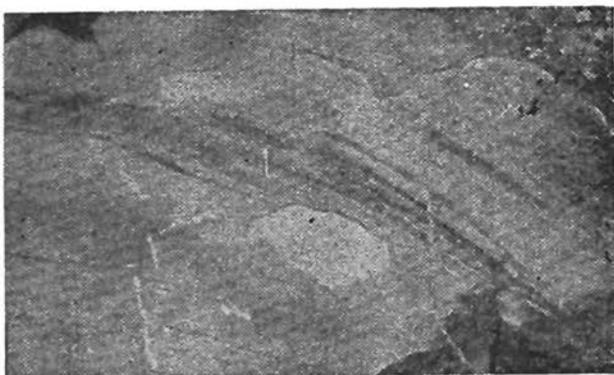


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Plate 2



A



B



C



D



A



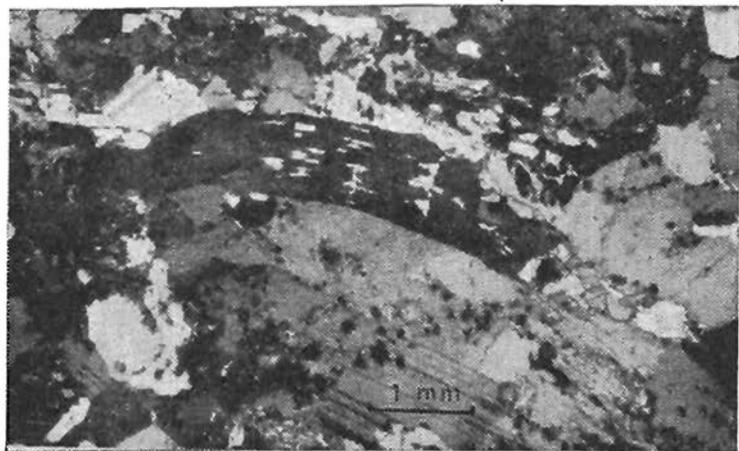
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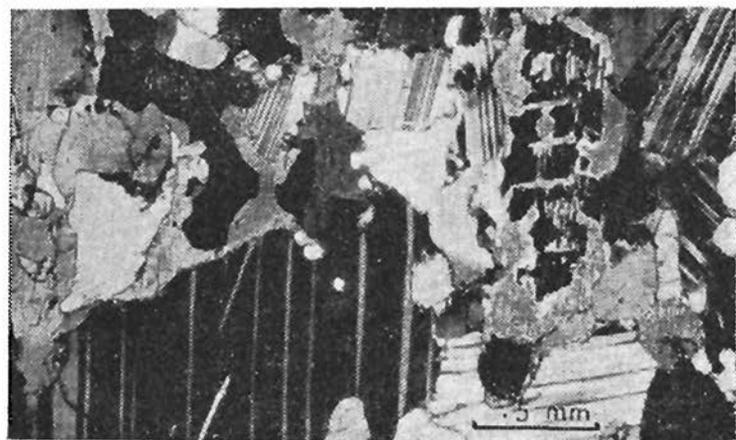
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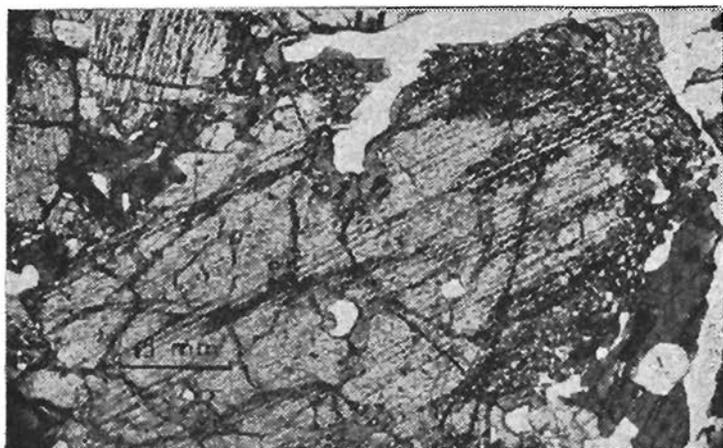
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A



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C

## PLATE 1

- A. Foliated granulite (US 14) near Bartana, Upper Swat, cut by a plagioclase-hornblende-pyroxene dyke that has granulitic metamorphic texture.
- B. Pyroxene granulite cut by hornblende-feldspar pegmatites. The central pegmatite seems to be finer grained on the margins, a feature not common to most of such pegmatites in Swat. Local patches of hornblende and a xenolith (near the hammer) are also present. Garhi stream, south of Bahren.
- C. Secondary hornblende veins in granulite near Madyan on the west side of the Swat river (From Jan and Kempe, 1973).

## PLATE 2

- A. Layered pyroxenite (dark) and norite in a pyroxenite zone near Pardesha (Madyan), Swat valley.
- B. Streaky layers of pyroxenite in norite to the south of Bahren, Swat valley.
- C. Pyroxene granulite (615) showing preferred orientation in plagioclase, and typical polygonal pyroxene. Some of the plagioclase grains (upper centre) are zoned and strained. Droplets of quartz in the large plagioclase grains are noticeable.
- D. Pyroxene granulite (197) with cloudy plagioclase showing a reduced number of twin lamellae and triple points. The plagioclase is separated from the hypersthene (fractured grain in the centre) by an inner colourless (? clinopyroxene) and an outer green (amphibole) envelope, and from the clinopyroxene (lower half) by an irregular epidote  $\pm$  amphibole envelope. These shells are thought to have formed due to a retrograde reaction between the plagioclase and pyroxenes.

## PLATE 3

- A. Intermediate member of the pyroxene granulites (US 14) showing intense granulation and bent plagioclase.
- B. Same as above. The large plagioclase could be metamorphic or pre-metamorphic (igneous); it is marginally zoned and has fewer twin lamellae than in the centre, and contains biotite 'inclusions' (in the right dark margin). Black patch is a fallen part of the section.

## PLATE 1

- A. Foliated granulite (US 14) near Bartana, Upper Swat, cut by a plagioclase-hornblende-pyroxene dyke that has granulitic metamorphic texture.
- B. Pyroxene granulite cut by hornblende-feldspar pegmatites. The central pegmatite seems to be finer grained on the margins, a feature not common to most of such pegmatites in Swat. Local patches of hornblende and a xenolith (near the hammer) are also present. Garhi stream, south of Bahren.
- C. Secondary hornblende veins in granulite near Madyan on the west side of the Swat river (From Jan and Kempe, 1973).

## PLATE 2

- A. Layered pyroxenite (dark) and norite in a pyroxenite zone near Pardesha (Madyan), Swat valley.
- B. Streaky layers of pyroxenite in norite to the south of Bahren, Swat valley.
- C. Pyroxene granulite (615) showing preferred orientation in plagioclase, and typical polygonal pyroxene. Some of the plagioclase grains (upper centre) are zoned and strained. Droplets of quartz in the large plagioclase grains are noticeable.
- D. Pyroxene granulite (197) with cloudy plagioclase showing a reduced number of twin lamellae and triple points. The plagioclase is separated from the hypersthene (fractured grain in the centre) by an inner colourless (? clinopyroxene) and an outer green (amphibole) envelope, and from the clinopyroxene (lower half) by an irregular epidote  $\pm$  amphibole envelope. These shells are thought to have formed due to a retrograde reaction between the plagioclase and pyroxenes.

## PLATE 3

- A. Intermediate member of the pyroxene granulites (US 14) showing intense granulation and bent plagioclase.
- B. Same as above. The large plagioclase could be metamorphic or pre-metamorphic (igneous); it is marginally zoned and has fewer twin lamellae than in the centre, and contains biotite 'inclusions' (in the right dark margin). Black patch is a fallen part of the section.